AFRL-SR-AR-TR-09-0086

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
27-02-2009	Final Report	June 2005 to November 2008

4. TITLE AND SUBTITLE
Micro-Propulsion Devices in Low Temperature Co-Fired Ceramics

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-05-1-0382

5c. PROGRAM ELEMENT NUMBER

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research/NA
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Arlington, VA 22203 - Dr Mitat Birkan

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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A hydrogen peroxide catalyst chamber was modeled and constructed. Four configurations were developed to determine the effect on reactor performance. The device inlet pressure and surface temperature were measured during a constant inlet mass flow rate of hydrogen peroxide propellant. The performance of the LTCC catalyst chamber and nozzle indicates that this technology can be used as a feasible micro-propulsion device.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*

FINAL REPORT

To: mitat.birkin@afosr.af.mil

Subject: Final Report, Contract/Grant # FA9550-05-1-0382

Contract/Grant Title: Micro-Propulsion Devices in Low Temperature Co-Fired Ceramics

Contract/Grant #: FA9550-05-1-0382

Reporting Period: 1 June 2005 to 31 November 2008

INTRODUCTION

In the satellite industry, the trend is towards decreasing size of satellites and clustering of these small satellites. Technological advancements in microelectronics have made it more economical to launch a cluster of satellites with a single vehicle rather than the traditional one satellite per vehicle. The smaller satellites have limited functionality and life span compared to the larger devices but they provide satellite operators the opportunity to increase redundancy and lower cost. In a distributed satellite cluster, the loss of a single satellite would not dramatically affect the overall performance of the cluster.

The smaller size of this new generation of satellites presents new operational requirements. A small satellite can not carry a large quantity of fuel or batteries for power. A small satellite may have to operate at a lower altitude to minimize transmission distances and will require an alternative propulsion system for station-keeping and orbital corrections. A large propulsion system is not effective in providing precision pointing in space, hence an alternative propulsion system is needed. The current micro-propulsion alternatives include miniaturized versions of Hall Effect thrusters, plasma thrusters and chemical devices. These devices are commonly fabricated as MEMS devices using silicon. The use of silicon presents several challenges including: limited thermal performance, only planar fabrication techniques and the ability to adhere a small number of materials to the surface. These limitations directly affect the ability to use silicon as a micro-propulsion material.

Low Temperature Co-Fired Ceramic (LTCC) materials are an alternative to silicon for micro-propulsion applications. LTCC uses cross-section ceramic tapes to build a device with internal fluidic channels in the green state. The device becomes a single monolithic structure after firing. Silver and gold pastes can be printed onto the individual layers allowing the metal traces to be distributed throughout the structure. The multi-layer structure provides a means to construct internal channels traversing many different layers. The ceramic structure is inherently resistant to high temperatures up to 1000K and reactive chemicals. Based on these capabilities, a micro-propulsion device was fabricated in LTCC device. The device was designed to decompose a monopropellant fluid through an internal catalyst chamber and direct the hot gases through a converging/diverging nozzle to produce thrust. Hydrogen peroxide was selected as a suitable monopropellant because of its decomposition temperature and catalytic response to silver.

Comprehensive Technical Summary

The development of a monopropellant micro-propulsion device in LTCC was approached in two sections. An LTCC nozzle was designed and analyzed using isentropic equations and a series of 3D CFD models. These results were compared to the experimental performance of the LTCC nozzle devices. To provide further validation of the nozzle performance, the nozzle exhaust plume was visualized using a schlieren system. The second area of development section was the design and testing of an internal catalyst chamber composed of a series of interconnected channels. Four devices were constructed with four distinct channel configurations. The devices were each tested by infusing propellant into the chamber at constant mass flow rate while measuring inlet pressure and surface temperature. Two studies of materials and processing characteristics were also initiated. The first study investigated the optimal processing parameters for embedding silver into the internal channels of the catalyst chamber with reliable channel dimensions after firing. The second experiment focused on the high temperature mechanical properties of LTCC to better understand the material performance during operation of the micro-propulsion device.

Nozzle Results

An LTCC device was designed and fabricated to demonstrate the ability to produce an effective converging/diverging nozzle using ceramic tape. Three nozzle sizes were developed based on three thrust levels: 325mN, 250mN and 200mN. Each nozzle was designed as an internal channel with a constant height of 1 layer or 0.2mm. The width of the channel was varied to produce the narrow throat and wider exit consistent with the hourglass shape of a convergent/divergent nozzle. The overall nozzle parameters were determined based on a one-dimensional, isentropic model for compressible flow. The isentropic parameters were used with a modified version of the Method of Characteristics to define the nozzle contour from the throat through the exit plane. The isentropic model was used to predict the ideal thrust, mass flow rate and specific impulse values for each nozzle at three pressures.

The generated nozzle curvature was exported and used to develop a solid model for fabrication. Three nozzle devices were fabricated using the LTCC process. A carbon tape insert was placed inside the internal cavities to prevent collapse during lamination of the stack of layers. The fired devices were inspected to determine the final size of the exit plane. The actual exit plane measurements were used to adjust the model data to the revised device size. Each of the nozzle devices was tested in a cold gas test fixture. Each test was conducted using a pressure controlled regulator based on a downstream pressure transducer. The thrust was measured with a load cell using a beam and fulcrum to amplify the signal. The mass flow rate, pressure and thrust were measured for each device at three pressure levels.

Three nozzle CFD models were developed using the 3D model geometry. A series of CFD tests was conducted to examine the nozzle performance using three different viscous modeling schemes for each pressure and nozzle configuration. An inviscid model was used as a comparison to the ideal isentropic model used in the nozzle development. A laminar model and a Spalart-Allmaras turbulent model were used as alternative viscosity treatments.

The results indicate that a planar converging diverging nozzle can be fabricated in LTCC materials. The thrust and mass flow rates of the fabricated nozzles were slightly less than the design values due to the variation in the size of the exit plane caused by shrinkage during firing.

Adjusted for the actual fabrication size, the ideal isentropic model predicts the thrust within 25.1%, the mass flow rate within 5.9% and the specific impulse within 18.2%. The ideal model neglects the viscous effects in the nozzle which cause the development of a boundary layer along the inner nozzle walls. The CFD models were developed to provide a better approximation of nozzle performance. The Spalart-Allmaras turbulence model predicts the thrust within 3.9%, the mass flow rate within 6.3% and the specific impulse within 8.5%. These bulk flow measurements indicate that the Spalart-Allmaras CFD model provides a good prediction of the performance of an LTCC nozzle.

A schlieren visualization system was developed to provide additional validation of the nozzle exit plume. The measured bulk flow properties describe the overall nozzle performance but they provide no information about the flow field. The schlieren system uses a Z-type configuration with an additional focusing lens to provide an image of the millimeter size nozzle plume. The shock waves and expansion waves in the nozzle plumes generate distinct patterns in the visual image of the plume produced by the schlieren system. These flow features are related to the density gradient along the axis of the plume. The plume images were compared to slices of the X-density gradient along the nozzle centerline using the CFD model data. The location of the shock waves downstream from the nozzle exit is a characteristic of the nozzle and operating conditions. Each viscous model was compared to the experimental image produced with the schlieren system. The Spalart-Allmaras consistently predicted the correct location and strength of the shock waves in the nozzle exhaust plume. Validation of the Spalart-Allmaras model allowed the observation of the flow field inside the nozzle using the CFD model. The model indicated a significant boundary layer developed along the nozzle sidewalls downstream of the throat. This boundary layer buildup effectively changes the area ratio of the nozzle by reducing the effective size of the exit plane area. This reduction in area ratio was seen in a reduction in exit Mach number and a subsequent reduction in thrust.

Catalyst Chamber

An analytical energy model was generated to predict the performance of a catalyst chamber developed in LTCC materials. An energy balance was generated to determine the theoretical decomposition temperature based on the generated chemical decomposition energy and the heat transfer out of the control volume. The model data was presented as a function of mass flow rate and concentration. For a 90% hydrogen peroxide mixture, a decomposition temperature of 1030K was predicted at a mass flow rate of 0.000102 kg/s. Hydrogen peroxide mixtures below 65% do not release enough energy to overcome the latent heat of the residual water and were limited to the saturation temperature of the residual water in the mixture. These temperatures fall within the capabilities of the LTCC materials system. The residence time for a 90% mixture of hydrogen peroxide was predicted to 0.003-0.005 s based on two published kinetic models. Based on the reaction kinetics and flow rates, a minimum catalyst chamber length of 15 mm was calculated. The feature sizes and operational conditions predicted by the analytical energy models indicate that a hydrogen peroxide catalyst chamber can be developed in LTCC.

Four catalyst chamber configurations were designed and fabricated based on the results from the analytical model. Each device was constructed with an inlet port, an inlet manifold, an exhaust manifold and a nozzle exit. The nozzle was used to restrict the mass flow through the device. A distance of 15 mm was specified between the manifolds as determined by the analytical model. Four variations of channels were fabricated spanning the space between the inlet manifold and the exhaust manifold. The configurations were chosen to determine the performance variations between using planar and multilayer channels. The configurations were also used to demonstrate the performance variations between straight channels and serpentine channels. These four devices were constructed using LTCC materials. The CNC direct write tool was used to apply the silver paste to the layers forming the channel walls. The paste was pre-laminated to flatten the silver surface prior to final assembly. Carbon tape inserts were used for the nozzle and manifold cavities during lamination. The catalyst chamber channels were left free of carbon and laminated at a lower pressure using a pressure sensitive adhesive to prevent collapse.

Each of the four catalyst chamber configurations was tested to determine the relative performance of each design. The testing was performed in a hydrogen peroxide test stand designed to safely deliver liquid propellant to the LTCC device while measuring inlet pressure and device surface temperature. Tests were conducted on each device using water, 30% hydrogen peroxide, 51% hydrogen peroxide and 63% hydrogen peroxide. 90% hydrogen peroxide was not available due to a shipping container issue. The 51% and 63% mixtures were created in the laboratory using an evaporation technique. Several different flow rates were tested for each device. At higher flow rates, the incoming propellant eventually flooded the catalyst chamber. The resulting temperature and pressure tended to increase with higher percentages of hydrogen peroxide.

Based on these tests, the 3D-2 configuration, which contains 6 layer changes for each channel through the catalyst chamber, produced the highest pressure at each flow rate and mixture. The 3D-2 configuration produced a maximum inlet pressure of 1342.4kPa and a surface temperature of 120°C at a flow rate of 14mL/min using the 63% mixture. The 3D-2 configuration also achieved a higher flow rate than the alternative configurations prior to flooding. The planar 2 configuration with serpentine channels outperformed the configuration with straight channels. Based on the results of the testing, the multi-layer channel configurations appear to outperform the planar channels.

The four catalyst chamber configurations were tested using 90% high test peroxide. These tests produced similar results to the tests using 30%, 51% and 63%. Overall, the measured temperatures on the surface of the device reached approximately 300°C. The multi-layer channel paths performed more effectively than the planar designs. During these tests, several failures were observed at higher temperatures and pressures. The failures appeared to initiate in the area near the catalyst chamber within the ceramic substrate. Based on a visual investigation of the failures, the most likely causes appear to be: thermal expansion in the region of the catalyst chamber, fabrication irregularities in the channels, and behavior of the LTCC materials system. These results led to further investigation of channel fabrication and high temperature LTCC behavior.

High Temperature Behavior of LTCC

The failure of the catalyst chamber at during testing with 90 % hydrogen peroxide led to an initial study of the high temperature behavior of LTCC. In addition, LTCC materials have potential application in other high devices such as high-temperature sensors, microfluidic devices and biomedical applications. Despite the strength that LTCC provides at lower temperatures, near the glass transition temperature the structural integrity of the substrate becomes a concern that requires further investigation.

For the micropropulsion device, an understanding of how LTCC behaves under a constant load and a high steady state temperature (steady state conditions) is important. In an attempt to find the most influential factors determining the deflection of LTCC in a micropropulsion device, experiments were conducted that more closely resemble the steady state conditions. [6]. A design of experiments approach was used. A screening experiment revealed: number of layers, temperature peak and dwell time at temperature peak as the three most influential factors. A subsequent test was conducted while only varying these three factors. Each part was placed under a constant load while the temperature was taken to its experimental value and held for the desired amount of time. The results show an increase in deflection as: 1) the experimental temperature peak was increased, and 2) the number of layers was decreased. A trend showing larger deflections with shorter dwell times suggests possible rebound occurring as the dwell time is increased. Although the set up for this experiment resembles steady state conditions, the purpose of the experiment did not involve the direct study of those conditions. Ongoing experiments are investigating the mechanical behavior of four commercial LTCC green tapes at elevated temperatures under steady state conditions.

Channel Deflection with Paste

The monopropellant micro-propulsion device used catalytic channels printed with silver paste embedded internally. Consistent construction of these channels depends on a wide range of variables both in the design and fabrication of the channel structure. By characterizing the final channel geometry when silver paste is applied to the upper and lower surfaces of an embedded single layer channel, accurate catalyst chambers were created. Application of silver paste to the upper and lower channel surfaces has been shown to alter the final shape of the channels within the test structure. Upper and lower surface deflection into the channel area was studied and characterization of this phenomena was illustrated as a function of channel width.

A design of experiment (DOE) method was used to explore how process parameters affect the channel geometry/integrity. Construction of the test structures includes the use of pressure sensitive adhesives and a sacrificial material to maintain the overall channel geometry/integrity. Lamination and firing profiles were modified in order to enhance this construction methodology. Techniques used to produce and characterize these channels were studied as well as the methods used to maintain channel geometry/integrity. The channel deflection in the sintered test structures was analyzed using optical microscopy and channel deflection across the width of the channels was determined. The average deflection between two channels of the same width was determined.

The data was plotted to determine how channel deflection changes with channel width and what effects PEOX, sacrificial carbon material and modified lamination pressure had on channel characteristics. The analysis of the channels demonstrated that the use of sacrificial carbon material reduced channel deflection when either lamination profile was used. The analysis also demonstrated that the use of PEOX did not have a significant effect on channel integrity when either lamination profile was used. However the use of PEOX remains important as it reduces the risk of the structure delaminating when using lower lamination pressures.

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SUMMARY

The smaller size of the new generation of satellites presents new operational requirements including a smaller propulsion system. Low Temperature Co-Fired Ceramics (LTCC) offers the advantages of multi-layered channels, high temperature capability and the ability to embed a variety of catalyst materials. A planar nozzle and hydrogen peroxide catalyst chamber was developed in LTCC for use as a micro-propulsion application.

Three supersonic nozzle configurations were developed and tested using the LTCC materials system. An isentropic model was generated to determine the overall size of each nozzle and the nozzle curvature was defined using a Method of Characteristics approach. Each nozzle was tested using a cold gas test stand at several pressures. The experimental thrust measurement was compared to the isentropic model and several 3D CFD models. The ideal model predicted the actual thrust to within 25.1%. The 3D CFD model using a Spalart-Allmaras turbulence model predicted the thrust to within 5.9%. A schlieren visualization system was created to further validate the CFD model results. The density gradient of the nozzle plume using the Spalart-Allmaras turbulence model matched the schlieren image of the shock locations in the nozzle exit plume.

A hydrogen peroxide catalyst chamber was modeled and constructed using the multi-layered capability of the LTCC. Four configurations were developed to determine the effect on reactor performance. The device inlet pressure and surface temperature were measured during a constant inlet mass flow rate of hydrogen peroxide propellant. An inlet pressure of 1342.4kPa and a surface temperature of 120°C were achieved at a flow rate of 14mL/min using 63% hydrogen peroxide. The multi-layer channel configurations achieved a higher inlet pressure for a given inlet flow rate compared to the planar designs. The multi-layer channel reactors also demonstrated a greater resistance to flooding at higher flow rates as compared to the planar design. The performance of the LTCC catalyst chamber and nozzle indicates that this technology can be used as a feasible micro-propulsion device.

Publications

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